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A Review of Wiring System Safety in Space Power Systems

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ABSTRACT

Wiring system failures have resulted from arc propagation in the wiring harnesses of current aerospace vehicles. These failures occur when the insulation becomes conductive upon the initiation of an arc. In some cases, the conductive path of the carbon arc track displays a high enough resistance such that the current is limited, and therefore may be difficult to detect using conventional circuit protection. Often, such wiring failures are not simply the result of insulation failure, but are due to a combination of wiring system factors. Inadequate circuit protection, unforgiving system designs, and careless maintenance procedures can contribute to a wiring system failure. This paper approaches the problem with respect to the overall wiring system, in order to determine what steps can be taken to improve the reliability, maintainability, and safety of space power systems. Power system technologies, system designs, and maintenance procedures which have led to past wiring system failures will be discussed. New technologies, design processes, and management techniques which may lead to improved wiring system safety will be introduced.

INTRODUCTION

The NASA Wiring for Space Applications program at NASA Lewis Research Center was initiated in response to the identification of arc-tracking as a possible result of improper use of polyimide insulated wire. The goal of the NASA Office of Safety and Mission Quality program is to determine the information and guidance needed to improve the safety and reliability of spacecraft wiring systems. In order to completely address the issue of wiring safety, not only must new insulations be developed, but the entire wiring system must also be considered.

The arc-tracking problem with polyimide insulation was first identified as an issue of concern in Navy aircraft [1]. A database of significant testing information for the use of alternative insulation constructions in aircraft was developed by the Air Force [2]. There are, however, environmental conditions typically experienced by NASA spacecraft, which the aircraft programs did not need to address. An interim report outlining the NASA operational environments was developed, and a testing program was begun to examine new insulation constructions in NASA spacecraft environmental conditions such as atomic oxygen, ultraviolet radiation, high vacuum, and thermal cycling [3,4].

The designing of wiring systems for spacecraft is a complex process. Many factors including the operational environment, electrical requirements, and the characteristics of the insulation to be used must be considered. Unless a wiring insulation is developed which will perform under all possible conditions, which is very unlikely, the wiring system factors must also be considered. Circuit protection technologies, design techniques, and maintenance procedures which will lead to improved safety should be identified.

In this paper, deficiencies in wiring system design, protection technology, and maintenance procedures which have contributed to wiring system failures in past NASA missions will be reviewed. New technologies for circuit protection which may reduce the risk of arc-tracking will be discussed. Future work involving new techniques for system design including systems engineering, concurrent engineering, and project management methods, which may lead to a higher quality process from design phase through operation and maintenance, will be introduced.

HISTORY OF SPACECRAFT WIRING SYSTEM FAILURES

In the history of NASA, there have been cases where failures in the spacecraft wiring systems have led to the failure of spacecraft components or even the entire mission. In most cases, wiring system failures are not due to a single failure, but occur as a result of multiple factors. These have included system designs which expose wires to unacceptable conditions, circuit protection technologies which didn't detect the fault, and maintenance procedures which led to wiring damage [5,6,7]. While a testing program is being conducted to investigate new insulation constructions and materials, the other contributors to failure must also be addressed. Examples of NASA spacecraft which have experienced wiring system failure, and the failure mechanisms which occurred will be discussed in this section.

Failures Influenced By Inadequate Technology

As previously stated, failures often have resulted from multiple factors which when combined result in a wiring fault. For example, under certain conditions the circuit protection devices currently in use may be ineffective in interrupting an arc-tracking fault. However, arc-tracking will not occur unless previously degraded polyimide insulation is being used [5,6,7]. In the case of the STS-28 Teleprinter cable short, a short circuit resulted due to polyimide insulation degradation (factor 1) which was caused by a bad connector design (factor 2). The short was not detected by the circuit breaker which was designed to protect the orbiter wiring from a continuous fault current (factor 3), because of the characteristics of the arc-tracking fault which occurred [6,8]. If the peak currents which occurred during this arc-tracking fault had been constant, their magnitude might have been high enough to trip the circuit breaker, which was rated at 10 Amps, and had a trip characteristic as shown in Figure 1. The total current of the arc-tracking fault, which is inconsistent as shown in Figure 2, because of intermittent arcing across the gap

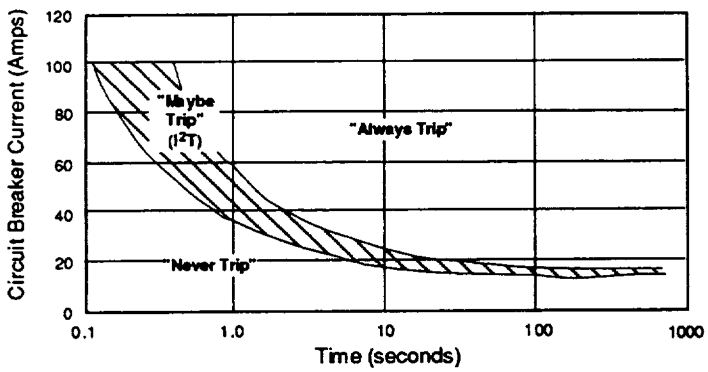

Figure 1. Thermal Circuit Breaker Trip Characteristics [6]

between conductors, averaged 30 Amps with spikes up to 50 amps [6]. Based on the total thermal energy in the circuit, current would have to flow through the breaker at a 30 Amp level for approximately 2.0 seconds to trip the circuit breaker, while a 50 Amp current would trip the circuit breaker after 0.5 second [9]. The teleprinter cable short did not trip the circuit breaker in this case because there was not enough thermal energy generated by the arc-tracking fault before it eventually extinguished itself [6].

In response to the ineffectiveness of this circuit breaker in detecting this fault, a test program at Johnson Space Center investigated the characteristics of the various circuit breakers, fuses, and Remote Power Controllers (RPC's) used for the shuttle program. The circuit protection limited the arc-tracking propagation to lengths of less than 1" up to 6" [5,10,11]. Due to the redundancy requirements of the space shuttle orbiters this level of protection is acceptable [12]. However, applying new technologies of fault detection to future spacecraft may improve the system safety.

Failures Resulting From System Design

There are also instances where the design of the wiring system contributed to its own failure. Two such cases are the STS-28 Teleprinter Cable, and the Apollo 13 Oxygen Tank Wiring System [6,13]. Although these failures have been corrected, it is important to analyze the types of failure mechanisms which have occurred in the past, to avoid similar failures in future systems.

STS-28 Teleprinter Cable

Damage to the polyimide insulation of the teleprinter cable was the result of the connector which extended straight out from the power panel requiring a sharp bend in the cable [6]. The repeated sharp bending of the wires over the back edge of the connector strain relief led to a circumferential break in the insulation [6].

The space shuttle program determined that because the failure was not detectable through pre-flight inspection or continuity and isolation testing, the connector was inappropriate for this application [6]. Therefore, changes were made and incorporated in subsequent missions. The

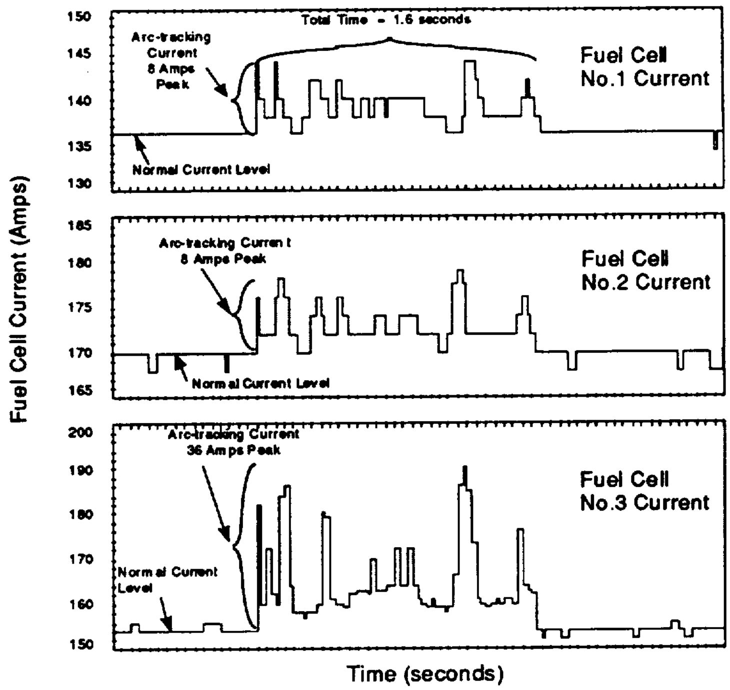

Figure 2. Fuel Cell Current During Arc-Tracking [6]

connectors which interface with the power supply panel were changed to have a 90° strain relief as shown in Figure 3. Additionally, the connectors were changed to a "clamp type" to accommodate strain relief sheathing, and the insulation was changed to Teflon to improve flexibility [5,6].

Apollo 13 Oxygen Tank

The wiring system design and a special "detanking" procedure required to empty the Apollo 13 oxygen tank led to wiring insulation degradation during ground testing. Failure of the wiring during the mission caused the oxygen tank to explode and threaten the lives of the three astronauts. Upon reviewing the failure, the Apollo 13 review board concluded that while the major features of the oxygen tank design were appropriate (Figure 4), specific design features were susceptible to failure [13]. The tanks contained potential ignition sources and excessive amounts of combustible materials which were present in the oxygen environment [13].

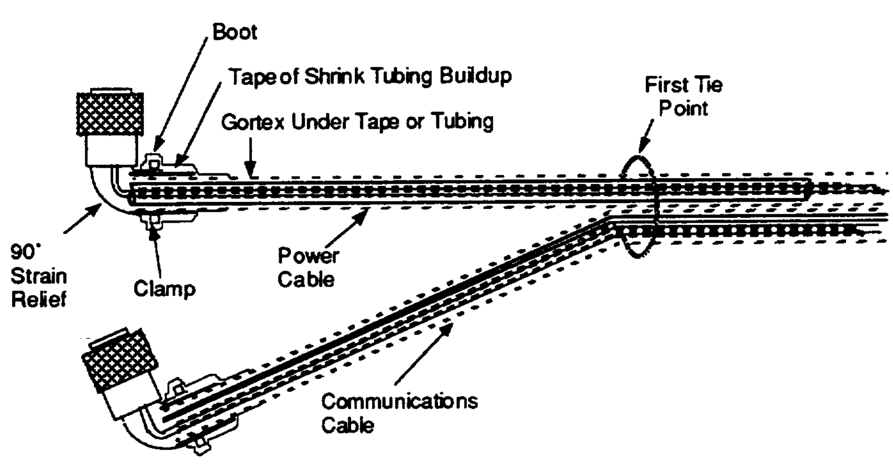

Figure 3. Teleprinter Cable Reconfiguration [6].

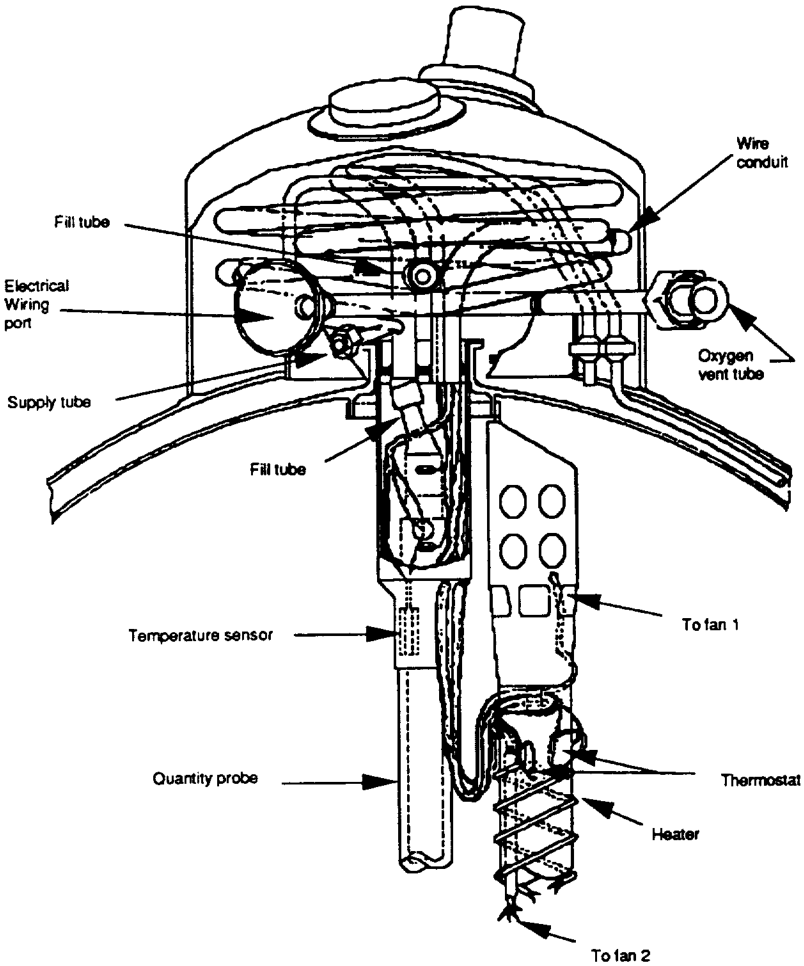

Figure 4. Oxygen Tank Wiring and Lines [13]

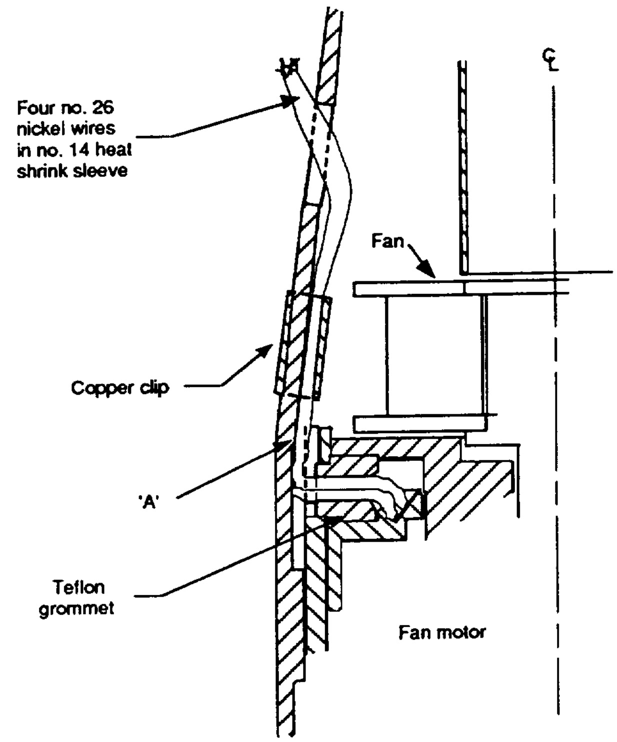

Figure 5. Typical wire routing for fan motor [13].

The design of the wiring for the oxygen tank fans was such that "cold flow" of the insulation (Teflon) when pressed against metal corners within the tank for an extended period of time, could eventually result in the degradation of the insulation [13]. As shown in Figure 5, a shrink fit Teflon tubing was used to encase the four 26 AWG wires which powered the fan motors and ran from the motor housing to outside the heater fan tube. This tubing provided protection for the wire bundle as it crossed the sharp machined edges of the heater tube access hole. However, the strain of the 90° bend of the wires at the motor housing was not eased by such protection. In addition, when the fan support tube was assembled, the wires may have been forced against the support tube edges at point 'A' in Figure 5 [13]. Furthermore, during the assembly process, the insulation of the electrical wiring inside the cryogenic storage tanks was exposed to relatively sharp metal edges. Finally, while wiring the tank, three bundles of six wires each were pulled sequentially through the conduit in the oxygen tank dome (Figure 4). The board found the size of this conduit was such that the last wires had to be forcibly pulled through the conduit [13]. As a result, damage to the wires in the conduit could have resulted which would not be detected without physical inspections (which were not possible with this design) [13]. Wiring system designs such as these can lead to failures not detectable by normal testing [13]. Fully considering wiring system failure in the system design process may improve the safety of wiring systems.

<u>Failures Due to Improper Maintenance Procedures</u>

The space shuttle orbiters, due to their reusability, must be serviced between each mission, and periodically major modifications and maintenance are performed. As a result, the condition of the wiring system is an important factor. The process of maintaining and operating the space shuttle orbiters has resulted in extreme mechanical stresses in areas where high levels of maintenance traffic occurs.

In general, wire damage has been a concern with the Space Shuttle Orbiters since the first mission of OV-102 (Columbia) at Kennedy Space Center in 1979 [6,14]. Major failures to the space shuttle orbiters have been avoided due to the redundancy and routing requirements, and the frequent wiring inspections which have identified and repaired many hazardous conditions. However, a failure related to mishandling of the wiring occurred on the STS-6 flight, which resulted in insulation pyrolysis and the melting of 6 conductors [15,16]. Failures also occurred on Magellan and Spacelab while being serviced [16,17,18].

There have been many occurrences of wiring system damage on the space shuttle orbiters, including an average of 1 short circuit per turnaround period attributable to the maintenance processes [19]. For example, between 1984 and 1985, there were 532

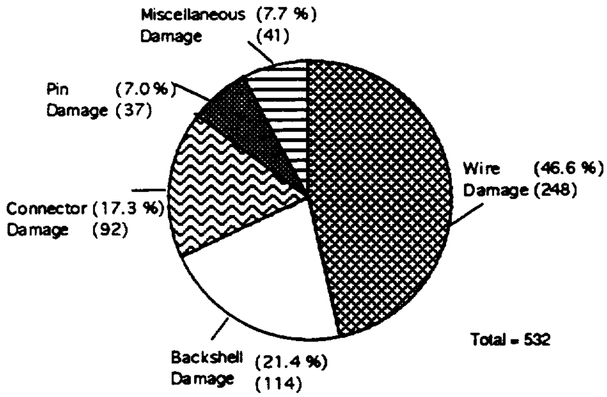

Figure 6. Breakdown of Wiring System Problems [14]

cable and connector problems reported on the fleet of shuttle orbiters [19]. These problems included damage to the electrical connectors, connector pins, backshells, and wires. The distribution of these problem occurrences are shown in Figure 6. In most cases, the shuttle maintenance practices led to the problems, with poor access, faulty connector design, and lightweight backshells also contributing to the failures [14].

Various inspections of the space shuttle wiring revealed that in general, the condition of the orbiter wiring was good, except for the areas with high levels of personnel traffic. In an effort to reduce wiring damage, formal training programs on the proper methods for handling, installing, and protecting the wiring have been developed for all the technicians, quality control inspectors, and electrical power system engineers who come into contact with the wiring systems [7,14,19,20]. It has been recommended that the assembly and maintenance procedures be analyzed and improved where necessary to further reduce the potential for wire damage [7,19].

Due to the high levels of personnel traffic, wiring congestion, and damage history, additional wiring protection has been added to selected wire harnesses in the Environmental Control Life Support System (ECLSS) bay and the aft fuselage area of the orbiters. The protection was added in two phases, the first phase was completed before each shuttle returned to flight, the second during major shuttle modification periods. The additional protection was of two major types, sheet metal covers to protect entire exposed areas, and convoluted tubing to shield smaller areas [7,14].

Equipment bays in the orbiters (i.e. ECLSS bay) have large quantities of wire, which are installed in wire trays. The equipment bays are also covered, further protecting the wires from damage. Therefore, the damage in the ECLSS bay was not extreme, and additional convoluted tubing was considered sufficient [21]. However, the aft fuselage wiring is routed directly on the sidewalls, as no wire trays were used due to their additional weight [19]. As a result, the aft fuselage areas required major modifications due to insulation damage. The aft fuselage External Tank (ET) sidewall (Figure 7) required replacement harnesses with convoluted tubing, split convoluted tubing to existing wires, and structural covers to shield the wiring from additional damage [5]. Other areas which required

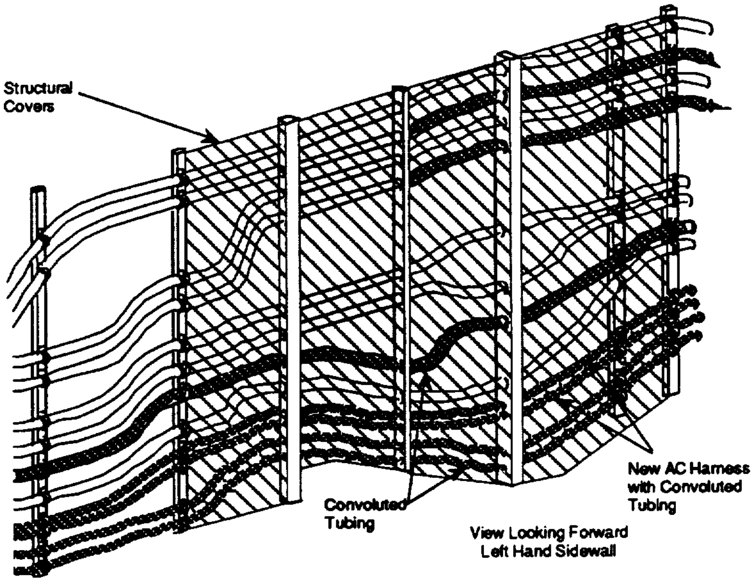

Figure 7. Aft Fuselage External Tank Sidewall [5]

structural covers in the aft compartment were the Vertical Engine Support System (VESS), the Main Engine Heat Shield, the Aft Fuselage Floor Area (OV-102 only), and the Aft Sidewalls [5,6,14].

Inspections performed after the physical protection was added revealed that the additional protection, rerouting, and elimination of sharp edges was sufficient to stop further damage from occurring. However, insulation degradation in high-traffic areas continued to be a safety issue for the space shuttle orbiters [19,22]. There was still concern regarding cases of misrouting, excessive tension on wires and connectors, improper installation, inadequate protection, and abuse during maintenance procedures. To continually assure that the space shuttle orbiters were safe, inspections were included as a part of the close-out process for all areas requiring maintenance during turnaround [7,19,20].

NEW WIRING SYSTEM TECHNOLOGIES

As shown previously in the case of the STS-28 teleprinter cable, common circuit breakers and RPC's are based on continuous overload currents and could be ineffective in detecting arc-tracking faults. Advanced circuit protection technologies may improve the detection accuracy. Many techniques which may improve circuit protection for spacecraft wiring systems have been identified [7], a number of these are discussed below.

Solid State Power Controllers

Circuit breakers which trip "instantly" upon the sensing of an overcurrent have been identified as a possible improvement in detecting arc-tracking. Solid State Power Controllers (SSPCs) are currently available which provide an "instant trip" capability. These devices have similar trip characteristics as electromechanical circuit breakers as shown in Figure 8, but can trip within about 25 μs of sensing a current of sufficient magnitude [23]. A possible problem with this method is that, in general the overcurrent must be $\geq 1000\%$ normal current rating

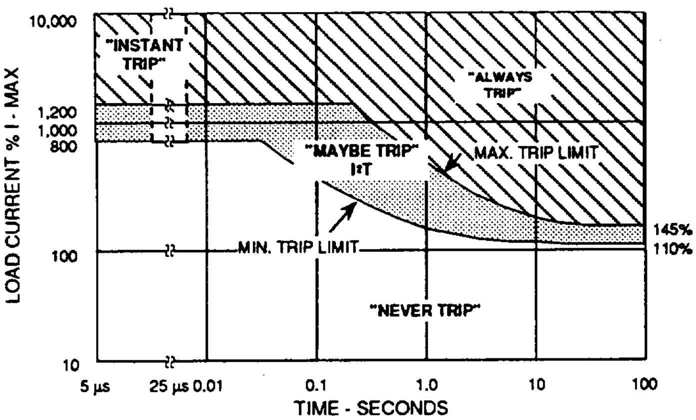

Figure 8. SSPC Trip Characteristics [23].

to trip instantly, which may be too high to detect even the peaks of the arc-tracking faults. Lowering this threshold may increase the likelihood of false alarms.

Dual-Element Time-Delay Fuses

Another currently available device which may improve the detection of faults is the dual-element fuse. A Dual-element time-delay fuse provides protection against temporary overload currents as well as sustained short-circuit currents. As shown in Figure 9, a dual-element fuse has a normal non-time-delay fuse to perform the short-circuit protection function, and an overload element which provides protection against low-level overcurrents or overloads. A typical dual element fuse will hold an overload which is five times greater than the ampere rating of the fuse for a minimum time of 10 seconds [24]. Further analysis and testing needs to be performed to determine the applicability of this device to space systems and arc-tracking.

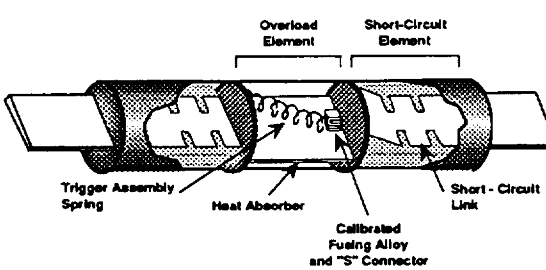

Figure 9. A Dual-Element Time-Delay Fuse [24].

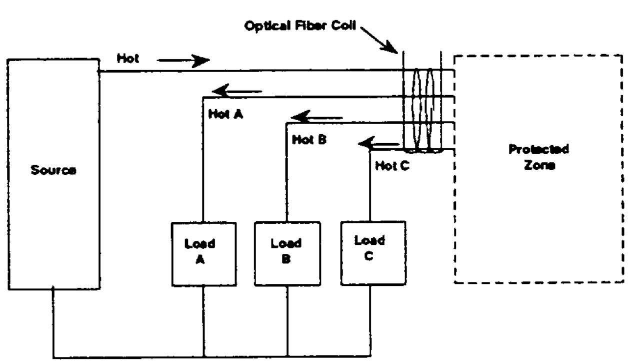

Figure 10. Zone Fault Detector Using Optical-Fiber Coil

Fiber Optic Current Sensor

Another proposed concept for detecting fault currents, including arc-tracking, in spacecraft wiring systems is to use a recently developed fiber optic current sensor (FOCS). Applying the FOCS in a differential current sensing mode could provide highly sensitive protection against fault currents. The FOCS, developed by the NASA Lewis Research Center and The National Institute of Standards and Technology (NIST) provides current sensing with immunity to Electromagnetic Interference (EMI), a wide bandwidth, a low mass, and excellent isolation [25,26]. The FOCS could detect faults through a zone-fault detection scheme as shown in Figure 10, where the currents entering and leaving the zone must be equal, or a fault is present. To use such a method again requires additional investigation and development.

"Intelligent" Fault Detection

For many years, in terrestrial and space power systems, methods of detecting incipient and low current faults in electrical power distribution systems have been investigated. Computer software based fault detection algorithms which attempt to identify faults via a "footprint" or "signature" of different failure modes offer possibilities of improved circuit protection. Faults can be detected for example, by identifying their unique energy characteristics or the "arcing signatures" [27]. These Autonomous Power System methods, and others, apply knowledge based "expert" systems which have the ability to "learn" and adapt to the unique characteristics of the system over time. Similar concepts involving neural networks and fuzzy logic control may also be applicable [28]. These concepts must be further developed and investigated for applicability to space power systems.

NEW SYSTEM DESIGN AND MANAGEMENT TECHNIQUES

Applying the methods of dynamic system engineering, concurrent engineering and total quality management to the design-manufacturing-maintenance processes of spacecraft wiring systems may eliminate many of the factors which contribute to wiring system failures. The entire process, from beginning to end, must be addressed, because as can be seen in existing cases of space shuttle payload manufacturing, despite design specifications which indicate otherwise, wiring systems are often installed using practices which are unacceptable [29]. To determine what, if any, improvements can be made, the current methods of system design, manufacturing, and maintenance need to be reviewed, and recent improvements documented. This type of analysis will be performed as a part of the NASA wiring program.

CONCLUSION

The NASA Wiring Program is an ongoing project to address the reliability, maintainability, and safety of spacecraft wiring systems. In addition to addressing the need for the development of new wiring insulation constructions for NASA spacecraft, the program is addressing the total system aspects of wiring safety. Occurrences of problems with wiring systems illustrate the need

to consider circuit protection, system design, and maintenance procedures in the discussion of wiring safety.

Improved circuit protection including the use of instantaneous trip circuit breakers, dual-element time-delay fuses, advanced fiber optic current sensors, and "intelligent" fault diagnosis methods may improve system safety by reducing or eliminating the effects of incipient and low current faults such as arc-tracking. These and other methods need to be addressed to determine the impact of their use in spacecraft wiring systems.

To fully address the safety of a space power wiring system, the entire life cycle of the spacecraft must be investigated. The engineer's design methods, the contractor's manufacturing processes, and the technician's maintenance techniques must all take into account the issue of spacecraft wiring system safety. Improvements in the wiring insulation combined with improved wiring system considerations will result in more reliable, maintainable, and safe spacecraft in future NASA missions.

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